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The Use of Reverse Osmosis for the Removal of As(III) and As(V) in Drinking Water

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<p>The following thesis project was designed to collect data on the use of reverse osmosis for arsenic removal in drinking water and to explore economic methods for sample analysis with emphasis on the use of an ion exchange resin for arsenic speciation. The data collected was meant for verification of existing results, finding an optimal operating point for the reverse osmosis unit provided by Malthe Winje DWS, and to determine whether double filtration by reverse osmosis increases the removal efficiency of As(III). Testing and analysis was conducted at the Norwegian University of Life Sciences, UMB (Ås, Norway).</p> <p>After analysis of results, it was determined that filtration by reverse osmosis can remove As(V) more efficiently than As(III). Operating the reverse osmosis unit at higher filtrate flows also results in higher removal rates of As. Lastly, while it was verified that reverse osmosis is an advanced treatment option for As removal, it was also determined that double filtration by reverse osmosis may not be a practical option for removal of As in drinking water.</p>	
Keywords	water treatment, reverse osmosis, arsenic(III), arsenic(V), arsenic speciation, ion exchange resin, DOW LP-4040, Malthe Winje DWS, drinking water, Norwegian University of Life Sciences

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1 Introduction

The quality of drinking water is a continuing issue around the world especially for those who do not benefit from having water treatment facilities or adequate water distribution networks. Arsenic-contaminated water is of special interest because of its cancer causing properties. While the World Health Organization has set limitations for arsenic in drinking water, arsenic-contaminated water remains an unaddressed threat in some regions. This is partly due to unavailable or expensive technologies for arsenic removal and costly analytical methods requiring trained professionals. This research focuses mainly on the use of reverse osmosis (RO) for As(III) and As(V) removal in drinking water.

Although RO use for arsenic removal has been studied extensively, this project was particularly interested in using the RO unit provided by Malthe Winje DWS in order to find the unit's optimal operating point and to determine whether Double Filtration by reverse osmosis is effective in removing larger concentrations of As(III). Close attention was also put on arsenic speciation -- in particular the use of an ion exchange resin -- since experiments conducted required arsenic speciation due to the fact that the water samples analyzed contained As(III) and As(V).

2 Drinking Water Quality

Drinking water typically comes from sources such as groundwater and surface water. Water coming from streams, lakes, rivers, and oceans are known as surface waters. Groundwater is water beneath the earth's surface, meaning that unlike surface water, groundwater is not in contact with the atmosphere. Because groundwater is continuously in contact with soil, it contains higher levels of dissolved minerals and other elements present in rocks. The source from which drinking water comes from determines what contaminants are present in it. For example, drinking water coming from a river may be contaminated with nitrates and phosphates that come from fertilizers used in surrounding farmlands. Consequently, the degree of water treatment largely depends on the source. Below is a brief overview of water quality parameters and corresponding treatment methods.

Clean household water should be clear and odorless. Therefore, any color or odor can easily indicate poor water quality. Color can vary from light yellow to dark brown; however, water can really be any color depending on the type of dissolved elements present. This is especially true of industrial or wastewater. Simplest methods of remediation include aeration for odor and filtration for color.

Color can also indicate the degree of turbidity in water (measured in Formazin Turbidity Units (FTU)) [1,116]. Usually clear water should have <1 FTU. Turbidity is dependent of the total insoluble contaminants in the water like algae, decaying organic material, clay, and silt. In water that is constantly moving, these insoluble elements will be seen as suspended particles in water. Only using filtration to improve the degree of turbidity is not enough to remove all of the suspended solids because such particles vary in size. An effective way to remove these is through flocculation and coagulation. With the aid of coagulant agents, particles are easily able to come together to form larger masses that be easily removed after sedimentation.

The concentration of dissolved gases is also a good indicator for determining water quality. Gases dissolved in water include oxygen, carbon dioxide, and ammonia. For drinking water, dissolved oxygen (DO) is a clear indicator of water quality since it affects taste. Low levels of DO are usually an indicator of poor water quality. The amount of DO in water comes from its diffusion from the atmosphere. Usually diffusion rate is very slow; therefore, aerators can be used for increased DO in water.

Acidity (pH) levels in the water indicate the type of contaminants present. Contaminants increasing acidity levels include carbon dioxide, sulfuric acid, and nitric acid, which can come in the form of acid rain caused by atmospheric pollution. Usually, pH adjustments are done chemically in order to meet standard pH levels for drinking water (these range from 6.5 – 8.5) [1, 83].

Another indicator of water quality is the conductivity. It reflects the concentration of ions present in water. Not all water sources have the same conductivity levels. For example, oceans have greater conductivity due to high salt concentration. Similarly, groundwater levels may differ from lake levels because groundwater is in contact with sediment and rocks that have charged elements. Conductivity in drinking water is typically measured in microSiemens per centimeter ($\mu\text{S}/\text{cm}$) [1, 49]. Adjusting the level of conductivity in-

volves technology that removes or adds ions to the water. For example, reverse osmosis technology is a method that is used to remove salts and other ions from water.

Another common quality parameter is hardness. In short, hardness is an indicator of the presence of specific ions (calcium and magnesium). For this reason, hardness in drinking water is usually measured in mg/L CaCO_3 [1, 58]. Levels of hardness depend on the water source. Generally, water is considered soft when the concentrations are less than 50 mg/L CaCO_3 and hard when concentrations are above 250 mg/L CaCO_3 [1, 58]. For other applications, it is ideal to maintain relevant hardness levels for the reason that high levels also cause incrustation within water distribution pipes. Water softening refers to reducing CaCO_3 concentration in water. Hardness can be adjusted by using technologies such as ion exchange or reverse osmosis.

Additional contaminants affecting water quality include the presence of heavy metals and inorganic elements like chloride, lead, fluoride, and arsenic. It is important to stress that the composition of water can be very dynamic; thus, remediation methods vary from one region to another.

3 Arsenic in Drinking Water

Arsenic (As) is a metalloid element occurring naturally in minerals, rocks, and soil. Its natural presence in the soil facilitates its movement through water sources such as groundwater. The concentration of arsenic varies per region and is influenced by anthropogenic activities such as mining. Despite its poisonous features, arsenic has desirable properties that make it a candidate for several industrial applications. Arsenic compounds can be found in semiconductors, wood preservatives, pesticides, and livestock feed. It's important to note that its acceptable use varies across countries. For example, the EU has clear limitations on the use and marketing of arsenic containing products and has banned the use of arsenic compounds in wood preservatives [2].

Overall, human exposure to arsenic compounds comes from contaminated water, food, and air polluted by industrial activities [3]. This is of special interest because in liquid form arsenic is odourless and transparent, making it impossible to detect by sight only. Arsenic is highly poisonous to humans with symptoms including abdominal pain, vomit-

ing, and muscular pain. In the worst case, arsenic poisoning leads to cancer and peripheral vascular disease [3].

Because some arsenic compounds have been identified as potent carcinogenics, many countries have set their own standards on the permissible levels of arsenic in drinking water. International standards of arsenic in drinking water are displayed in Table 1. The World Health Organization (WHO) has been known to establish standards for arsenic in drinking water since 1958. One of the earlier standards established in 1963 allowed a concentration of only 50 $\mu\text{g/L}$ As [4, 202]. Today, the permissible WHO standard is 10 $\mu\text{g/L}$ and is accepted by most European countries and the United States.

Table 1. World Guidelines for Arsenic in Drinking Water [4, 206]

Guideline	Countries
< 10 $\mu\text{g/L}$	Australia (7 $\mu\text{g/L}$)
10 $\mu\text{g/L}$	European Union (1998) Japan (1993) Jordan (1991) Laos (1999) Laos, Mongolia (1998) Namibia, Syria (1994) United States (2001) Canada (2006)
25 $\mu\text{g/L}$	Mexico (2005) [5]
50 $\mu\text{g/L}$	Most of all remaining countries follow this standard or are reviewing it.

Having a uniform limit throughout the world is quite difficult since areas where arsenic concentrations are high are areas that do not have the means for advanced water treatment or access to analytical technologies. Figure 1 shows a map compiled by WHO with regions affected by high arsenic concentrations and arsenic poisoning.

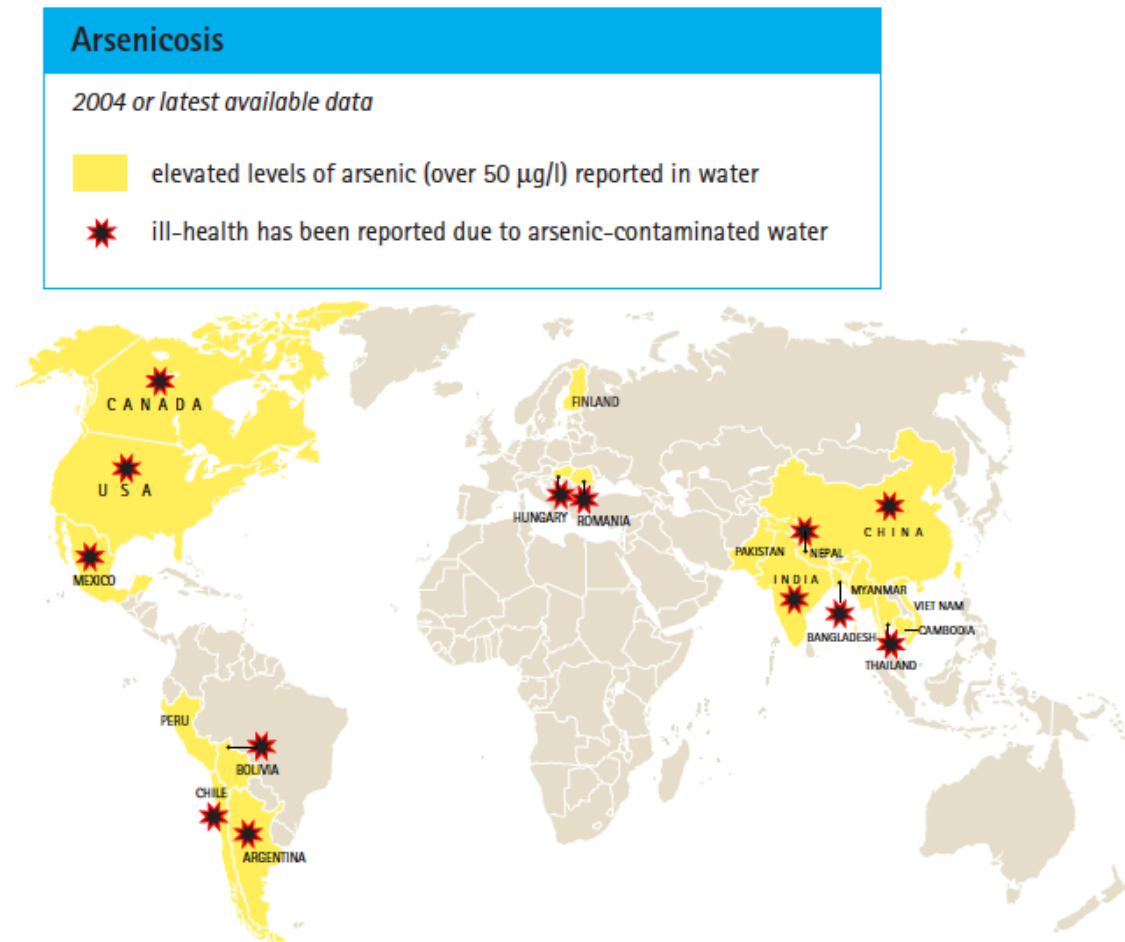


Figure 1. Arsenic in Drinking-Water Worldwide [6]

4 Chemical Properties of Arsenic

In the environment, arsenic has several oxidation states (-3, 0, 3 and 5) and exists in both organic and inorganic forms. However, for the purposes of this study, only trivalent arsenite (As(III)) and pentavalent arsenate (As(V)) were examined because these are the forms of arsenic most prevalent in sources of drinking water. It is well known that As(V) is more abundant in surface water than in groundwater [7]. As seen in Figure 2, As(V) and As(III) can exist in several forms depending on pH levels. For example, in surface waters with pH from 5 – 8, arsenate exists as an anion (H_2AsO_4^- or HAsO_4^{2-}) [7]. Naturally, As(III) is more abundant in groundwater in the neutral form, H_3AsO_3 [7].

Besides its natural occurrence in the environment, arsenic has become a cause of concern due to its ability to convert into different species of arsenic over different pH levels in oxidizing and reducing conditions. Figure 2 illustrates the type of arsenic spe-

cies present at different pH levels and its corresponding redox potential. It can be observed that at normal pH levels of drinking water, H_2AsO_4^- , HAsO_4^{2-} and H_3AsO_3 are dominant species. For removal purposes this is significant because the species' charge determines the type of removal method that can be used. However, arsenic removal can be a challenge because, as Figure 2 illustrates, under the correct conditions, oxidation or reduction can convert the species and render the selected treatment ineffective.

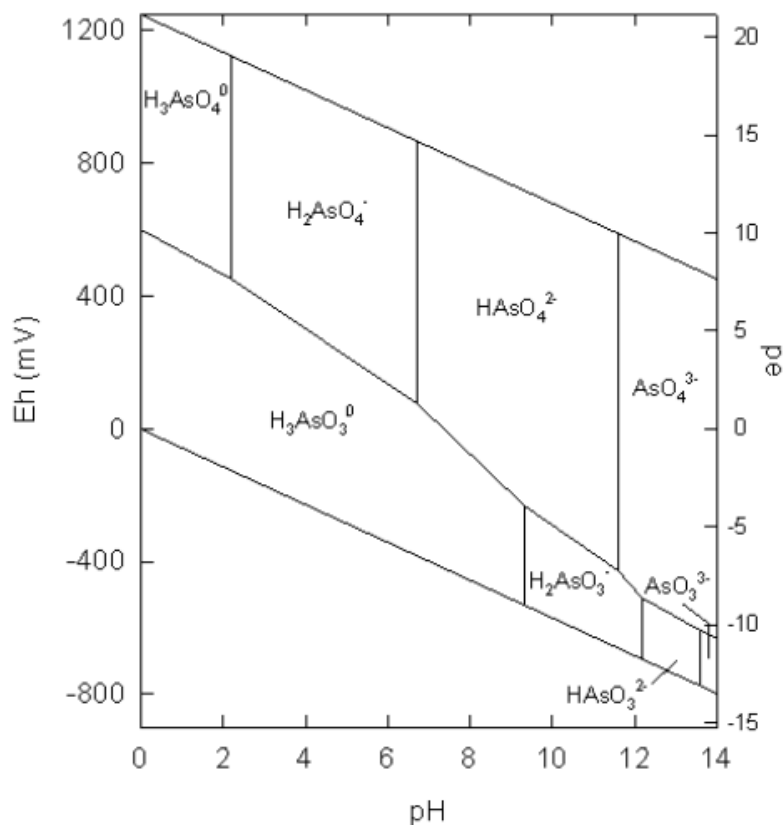


Figure 2. Eh-pH Aqueous Arsenic at 25 °C and 1 bar total pressure [8,4].

5 Available Technologies for Arsenic Removal

There are several technologies available for arsenic removal. However, their use is often limited due to economic and operational reasons. These limitations are clear reasons as to why not all countries meet the WHO standard of 10 $\mu\text{g/L}$. It is important to note that even while using the best technology available, total arsenic removal can be a challenge and traces of arsenic below the standard may still be present in drinking water. In addition, even if the arsenic is removed from drinking water, the arsenic-

concentrated effluent still requires appropriate treatment and disposal. This can often prove to be both time-consuming and expensive.

The following paragraphs briefly discuss the main technologies available for arsenic removal – including the use of reverse osmosis and ion exchange resins -- followed by their advantages and disadvantages.

5.1 Oxidation

The most inexpensive As removal treatment is atmospheric oxidation which can be done by static aeration or with the aid of sprinklers. While it is the most economic treatment, it is also the most time consuming and in some cases too slow to meet the demands of clean water. Aeration can remove some unwanted contaminants such as odor, radon, and As(III). Removal of As(III) through aeration does not mean the removal of total arsenic but conversion of As(III) to As(V) which happens to be more effectively removed by other technologies. In short, oxidation/aeration treatment is a cost-effective preliminary step to arsenic removal.

Chemical oxidation is a faster and a more efficient alternative to atmospheric oxidation. However, such method requires the use of oxidizing chemicals, sludge treatment, and constant pH monitoring. Chemical oxidation can be an advantageous preliminary method because it is through proper oxidation that As(III) is converted into As(V) [9, 253]. Such conversion is preferred because the removal of As(III) is more difficult than As(V) – as will be proven in this research.

5.2 Coagulation

Coagulation and flocculation are also alternative methods for arsenic removal. Like other removal technologies, coagulation methods are not as efficient at removing As(III) than they are for As(V) [10]. Coagulation chemicals include: alum, lime, and iron. As with chemical oxidation, the use of coagulation also requires adjusting the pH to reach optimal removal efficiency. This will depend on the coagulant agent being used and the concentration of arsenic initially present in the water [10]. Disadvantages of this method include having access to appropriate coagulants, being able to dispose of the concentrated sludge in a safe manner, and possibly re-adjusting pH to normal levels (this step requires additional chemicals).

5.3 Adsorption and Ion Exchange Technology

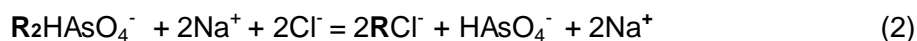
In the water treatment process, adsorption removal technologies use materials such as ion exchange resins, iron-coated sand, activated carbon, and activated alumina to remove impurities from water. While such technology is effective, it can be very expensive, thus making it inaccessible to developing countries with arsenic problems. After constant use, adsorption mediums also become saturated and need regular maintenance and regeneration that can only be achieved by the use of their corresponding regeneration chemicals and appropriate effluent disposal. Not all adsorption mediums can be regenerated and even if they can, it is possible that they lose some of its treatment abilities. For example, a single regeneration of activated alumina often decreases its effectiveness by 30 – 40% [9]. Because this research utilized an ion exchange technology for analytical purposes, the fundamentals of such technology will be discussed here in more detail.

Ion exchange technology uses a material such as a charged synthetic resin to interchange ions between itself and liquid passing through it. In this way, charged impurities in water are retained and replaced by the ions adsorbed to the resin. Ion exchange resins are usually manufactured for the removal of specific ions/contaminants. In the case of arsenic removal, it is important to note that ion exchange resins are only effective in removing As(V). The type of resin required for As(V) removal is a strong base anion exchange resin which is loaded with chloride ions. The ion exchange process can be written as follows:



As shown by this reaction, the anion resin (**R**) is loaded with chloride ions that are interchanged with similar charged ions like HAsO_4^- (As(V)). The resulting product is a resin loaded with HAsO_4^- and product water containing extra chloride.

After extensive use, the resin becomes saturated and ineffective in removing additional As(V). Depending on the type of resin, regeneration or replacement is required. For a strong anion exchange resin loaded with Cl^- , regeneration can be carried out using the same ion exchange principle with the aid of NaCl^- . The process can be written as follows:



Thus, through this reaction, the resin is brought back to its original state and can be reused.

One of the disadvantages of this method and all other adsorbents is that they can be expensive and require maintenance. Resin effectiveness is also dependent on the type of resin, contaminant, and other ions present in the water. For example, when treating As in drinking-water, contaminants found in surface water such as sulphate and nitrogen are just as likely to adsorb to the resin as As(V) [11]. Thus, a high concentration of similar contaminants will affect the removal rate of the target contaminant.

It is also possible to use ion exchange resins for analytical purposes. For this research, speciation analysis was done by passing As(III) and As(V) contaminated water through the resin. Further details about speciation analysis using ion exchange resins are found in section 6 Analytical Methods for Arsenic in Water.

5.4 Reverse Osmosis

Along with ion exchange, reverse osmosis (RO) is used for advanced treatment. RO technology makes the use of synthetic membranes made of polyamide to produce ultra pure water for both drinking and industrial purposes. A polyamide membrane, such as the one used in this research, is composed of three layers that determine its efficiency [11]:

1. A very thin selective polyamide layer.
2. Microporous polysulfone support layer.
3. Non-woven fabric layer.

Along with the pressure applied to the membrane, its performance is influenced by the chemical and physical composition of its surface. For instance, in the case of As removal, it is important to note that the membrane's surface charge is negative [13]. It is important because as is shown in Figure 2, arsenate anions (As(V)) exist in all possible drinking water pH ranges. A negatively charged membrane enables the removal of negatively charged contaminants, including As(V).

The RO membrane used is shaped into a spirally wound cylinder (Figure 3). With a certain amount of pressure, water first passes parallel to the membrane. Contaminants

are removed from the water with the help of applied pressure, difference in solute concentration (from high to low), and surface membrane charge. As water passes, the target contaminants (concentrate) remain outside of the membrane and the rest of the water (permeate) passes through the membrane in a spiral direction until it ends up in the middle pipe inside the membrane ready to be collected for use or further treatment.

In the case of As(V) removal, as water passes spirally through the membrane, the surface charge of the membrane repels the negatively charged As(V). This means that present As(III) will continue to travel spirally through the membrane and to the permeate pipe while the As(V) concentrate is repelled and remains outside the membrane as it passes to the effluent pipe.

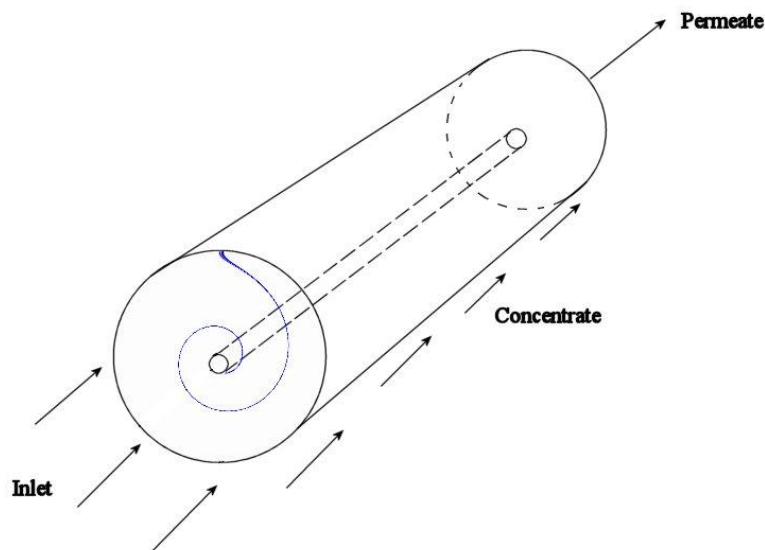


Figure 3. Simplified RO Membrane Module

One advantage of RO treatment is that it does not require a large treatment plant and can be used for domestic purposes when paired with filters. However, one of the drawbacks includes membrane fouling and maintenance (especially when dealing with larger RO units). Membrane fouling is of importance due to membrane costs and rapidly declining performance. Contaminants causing membrane fouling are soluble salts, biological growth, dissolved organic compounds, and suspended particles [14]. Of these four membrane contaminants, dissolved compounds and suspended particles affect the membrane's lifetime the most because they are the hardest to remove [14]. It is

also for this reason that RO units should be used with pre-filters to avoid membrane clogging.

6 Analytical Methods for Arsenic in Water

Methods available for arsenic analysis depend on the medium being analyzed. For water, there are several methods that mostly focus on the detection of total arsenic (Table 2). When dealing with water contaminated with both As(III) and As(V), identifying specific quantities of each becomes a problem. The analytical method selected also depends on the detection limit desired. Since the WHO limitation is 10 µg/L As in drinking water, the analytical method selected should be able to detect such magnitude.

Table 2. Commonly Used Analytical Methods for Arsenic [15].

Method	Detection	Detection Limit
Colorimetric/spectrophotometric methods	Total Arsenic	~ 40 µg/L
Inductively coupled plasma – atomic emission spectrometry (ICP – AES)	Total Arsenic	~ 30 µg/L
Inductively coupled plasma – mass spectrometry (ICP – MS)	Total Arsenic	0.1 µg/L
High resolution (HR)-ICP-MS	Total Arsenic	0.01 µg/L
Graphite furnace – atomic absorption spectrometry (GF – AAS)	Total arsenic	0.025 µg/L
Hydride generation – atomic absorption spectrometry (HG-AAS)	Total arsenic and arsenic speciation	0.6 – 6 µg/L
Hydride generation quartz furnace – atomic absorption spectrometry (HG-QF-AAS)	Total arsenic and arsenic speciation	0.003 – 0.015 µg/L
HPLC or solid phase cartridge separation combined with hydride generation-atomic fluorescence spectrometry (HPLC-HG-AFS)	Arsenic Speciation	0.05 – 0.8 µg/L
HPLC-ICP-MS	Total arsenic	0.01 µg/L

Inductively coupled plasma – mass spectrometry (ICP – MS) and a strong base anion exchange resin were used in this research to determine arsenic concentrations in each sample. In experiments where only As(III) was used, ICP – MS was the only detection method used. On the other hand, in experiments where As(III) and As(V) were combined, a strong base ion exchange resin was used to separate As(V) from As(III) in a sample. This method is only for separation and is followed by ICP – MS for actual determination of arsenic in the sample. Figure 4 illustrates the procedure carried out to determine arsenic concentrations in samples containing As(V) and As(III).

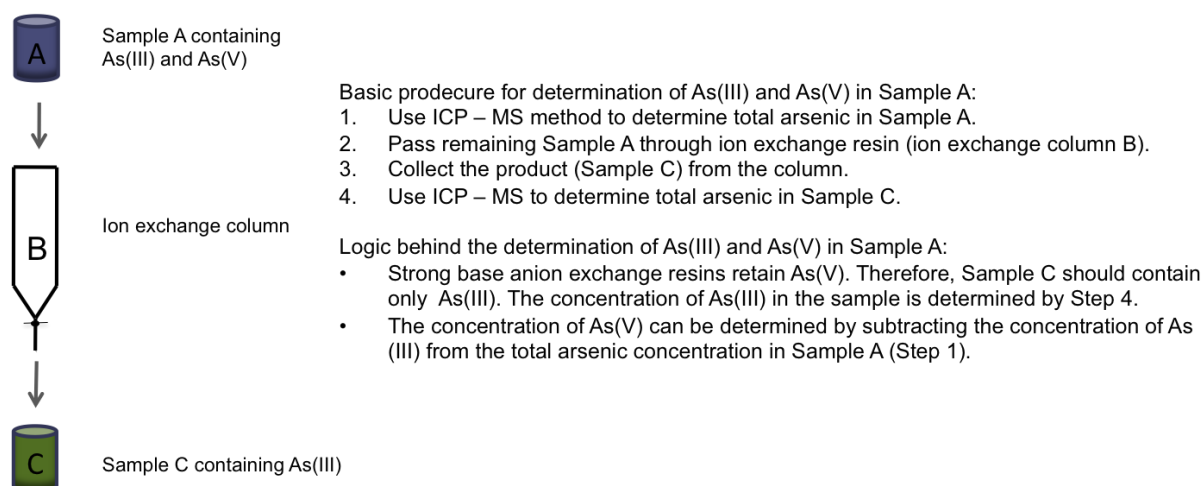


Figure 4. Determination of As(III) and As(V) concentrations in one sample.

7 Observed Challenges and Objective

The main challenge when dealing with arsenic-contaminated water or poor quality water is that regions affected by this problem lack the adequate standards to improve the situation. Even if there are possibilities of improving the quality, it does not mean that emphasis will be put on improving it or removing dangerous traces of arsenic. For example, countries like Finland and USA (reporting traces of arsenic in water sources) are not developing countries that have a considerable lack of treatment technology. However, the main difference between both is that in Finland the quality of drinking water from the tap is so high that it can be directly consumed without filtration or additional treatment. In USA, however, it is not encouraged to drink water from the tap as it may contain traces of unhealthy contaminants. In addition, as shown in Figure 1, there are traces of As in water sources in both regions, but only in the USA have there been reported cases of poor health due to arsenic poisoning.

The challenge is a combination of awareness, available treatment technology, and willingness to remediate the problem. For these cases, the first goal would be to make available treatment units that are economic and easily maintained. Affected regions requiring treatment units should have corresponding analytical technology available to ensure that their treatment units are operating well.

This thesis project was focused on finding an optimal operating point for a medium-sized RO unit provided by Malthé Winje DWS. The unit, along with the chosen RO membrane, was run at different filtrate flows to determine the best operating flow that

would remove larger quantities of As. In addition, because it is known that As(III) removal rates for RO systems are not as successful as those of As(V), passing As(III) contaminated water twice through the RO unit (what is referred to in this document as Double Filtration) was done to determine if it is possible to remove more As(III) without adding an additional step to the treatment process.

Finding an economic way of analyzing concentrations of As(III) and As(V) found in one water sample was also explored by utilizing an ion exchange resin for separation purposes and ICP – MS for analyzing total arsenic in samples.

8 Selection of Methods and Materials

8.1 Components of Input Raw Water

This research was carried out using normal tap water. For each experiment, different concentrations of As(V), As(III), and combinations of As(III) and As(V) were added. No other chemicals were added for pH adjustment. The concentrations used were 50 µg/L As(III), 200 µg/L, and 100 µg/L As(III) plus 100 µg/L As(V). Additional information about the experimental procedure and conditions is found in section 9.3 Experimental Procedure.

8.2 Reverse Osmosis Unit

Malthe Winje DWS provided the RO unit used. Figure 5 displays a piping and instrumentation diagram of the unit.

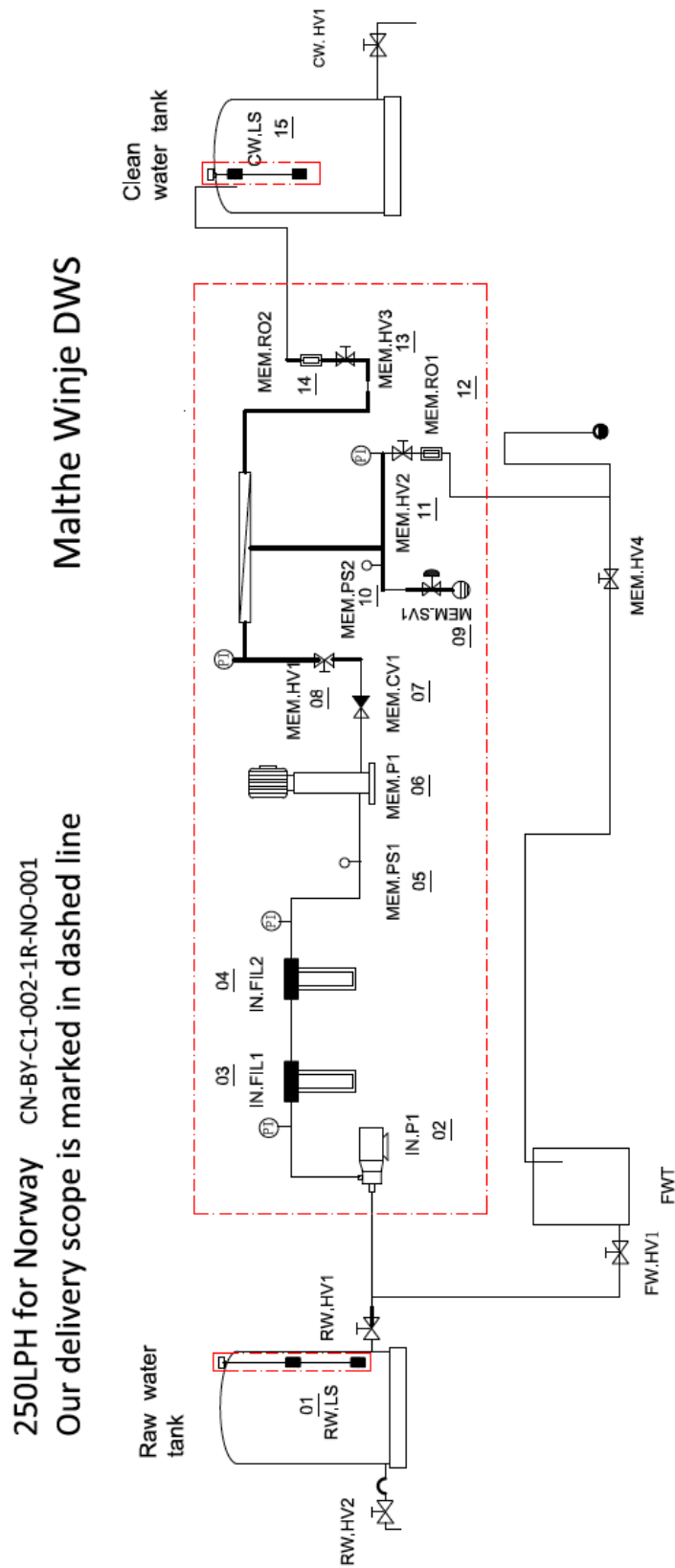


Figure 5. P & ID RO Unit CN-BY-C1-002-1R-NO-001

8.3 Reverse Osmosis Membrane

RO membrane selected was DOW FILMTEC LP-4040. This is a tape element meant for commercial applications. According to DOW [16], it is meant to deliver “high quality water at low-pressure operation”. As mentioned in the product specifications found in Appendix 1, this membrane is made of polyamide thin-film composite and has a salt rejection of 99.2 %. It has a wide pH operating range and can tolerate operating pressure of up to 41 bars.

8.4 Ion Exchange Resin and ICP-MS

Analysis using ICP – MS were carried out separately in another laboratory at the Norwegian University of Life Sciences (UMB). The ion exchange selected was a DOWEX 21K XLT Strong Base Anion Exchange resin suitable for mining applications. It is a Type I resin delivered in the Cl^- for with a possibility for resin generation using NaCl . Product specifications are found in Appendix 2.

9 Experimental Design

9.1 Limitations

Finding economical solutions for testing and analysis were the biggest limitations for this research. The experiments conducted were only six because there were only enough funds for analyzing one-hundred samples. In order to acquire reliable data, the number of samples taken per experiment ranged from six to fourteen. The total number of samples taken was fifty-five which includes two samples for testing of the ion exchange resin and two samples for exploring the conversion rate of As(III) to As(V) during aeration treatment.

Further experiments were not conducted after taking the fifty-fifth sample due to technical difficulties with analytical equipment – mainly the ICP – MS equipment in the laboratory. In addition, because the RO unit used is not in constant operation and is only used for pilot testing, a lot of maintenance had to be done in order to prepare it for the experiments. This may have affected the final results.

9.2 Experimental Procedure and Conditions

A detailed description of the experimental procedure can be found in Appendix 3 and 4. Table 3 lists the experiments conducted and displays the experimental conditions.

Table 3. Experimental Conditions.

Experiment	Conditions		Filtrate Flow
1	RO Treatment	50 µg/L As(III)	100 L/h
2	RO Treatment	200 µg/L As(III)	100 L/h
3	RO Treatment	50 µg/L As(III)	350 L/h
4	RO Treatment	200 µg/L As(III)	350 L/h
5	RO Treatment	100 µg/L As(III) + 100 µg/L As(V)	100 L/h
6	RO Treatment	100 µg/L As(III) + 100 µg/L As(V)	350 L/h
7	Aeration Treatment – 24 hours	100 µg/L As(III) + 100 µg/L As(V)	
8	Aeration Treatment – 24 hours	200 µg/L As(III)	

All experiments were subjected to double filtration, constant pH, and same source of tap water. Filtrate flow refers to adjusted treated water flow and can be seen in Figure 5 as MEM.RO2. In addition to filtrate flow, during normal operation, effluent flow is the only other output in this system and can be seen in Figure 5 as MEM.RO1. Lastly, the object MEM.P1 in Figure 5 represents a membrane pump that continually pumps a constant 1 m³/h of water into the membrane.

10 Results and Discussion

10.1 Experiments 1 – 4

The results for the first four experiments are discussed first because they only involve RO treatment of As(III). The main goal was to determine the effect of filtrate flow on the removal of As(III) and the total removal of As(III) after double filtration. It is important to mention that during raw water preparation, exact volumes of As(III) were measured and added to the raw water to match the corresponding concentration; however, a sample of the raw water was still taken and analyzed in order to determine the actual concentration of the inlet. Table 4 shows the target and actual inlet concentrations of As(III) and removed As(III) in Filtrate I. All of the following calculations use the actual measured concentration of the inlet.

Table 4. Removed As(III) in Filtrate I

Filtrate Flow [L/h]	Target Inlet Concentration As(III) [$\mu\text{g/L}$]	Actual Inlet Concentration As(III) [$\mu\text{g/L}$]	Average Filtrate I Concentration [$\mu\text{g/L}$]	Removed As(III) in Filtrate I
100	50	48	16	66%
100	200	193	66	66%
350	50	50	11	79%
350	200	194	39	80%

The actual inlet concentrations were on average about 3% off from the intended concentrations. It is clear from these results that operating the RO unit at a larger filtrate flow will remove more of the arsenic regardless of the concentration in the inlet. However, despite of up to 80% As(III) removal at 350 L/h filtrate flow, the resulting drinking water is not adequate for consumption since the WHO limit is 10 $\mu\text{g/L}$ and the resulting water contained 11 and 39 $\mu\text{g/L}$ As(III). The results also suggest that regardless of the concentration, the filtrate flow largely dictates the removed As(III). For example, experiments with filtrate flow of 100 L/h had a removal rate of 66% even though the concentration was 50 $\mu\text{g/L}$ As(III) for one experiment and 200 $\mu\text{g/L}$ As(III) for the other.

Table 5. Total As(III) Removal Rates (Results of Double Filtration)

Filtrate Flow [L/h]	Initial Concentration As(III) [$\mu\text{g/L}$]	Inlet Concentration (Filtrate I) As(III) [$\mu\text{g/L}$]	Average Filtrate II Concentration [$\mu\text{g/L}$]	Removed As(III) in Filtrate II	Total As(III) Removal after Double Filtration
100	48	16	4.1	75%	91%
100	193	66	22	67%	89%
350	50	11	1.3	88%	97%
350	194	39	5.0	87%	97%

Table 5 presents As(III) removed after Filtrate I had been passed through the RO system again (Double Filtration). Effectively, Table 4 and 5 are results of one continuous experiment. The initial concentration shown in Table 4 is also in Table 5 to show the magnitude of the total As(III) removed after Double Filtration. If removed As(III) in filtrate II is analysed independently, then the results also confirm that at 100 L/h, the removal rate is lower (average of 69% removal) than at 350 L/h (average of 84 %). Figure 6 and Figure 7 provide graphical representations of the results.

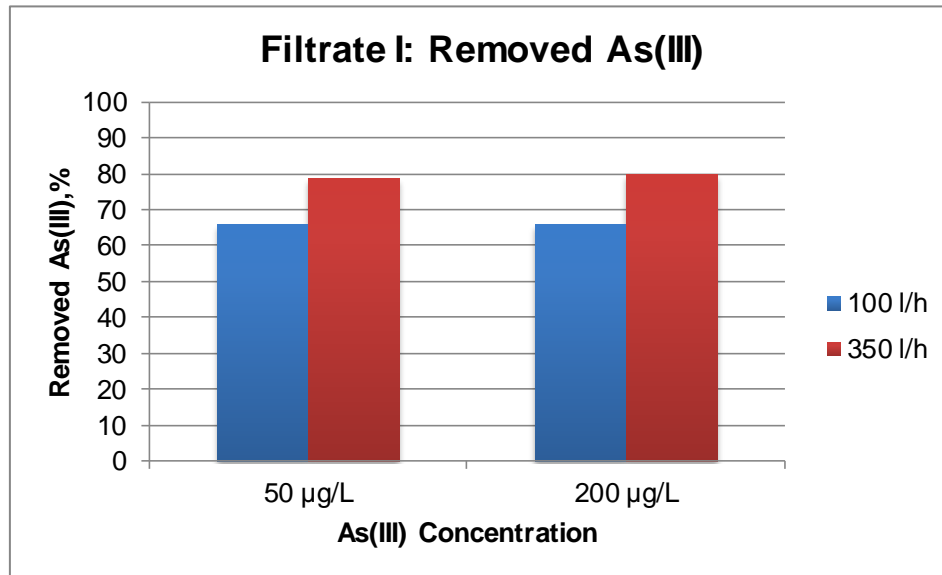


Figure 6. Total As(III) removed in Filtrate I

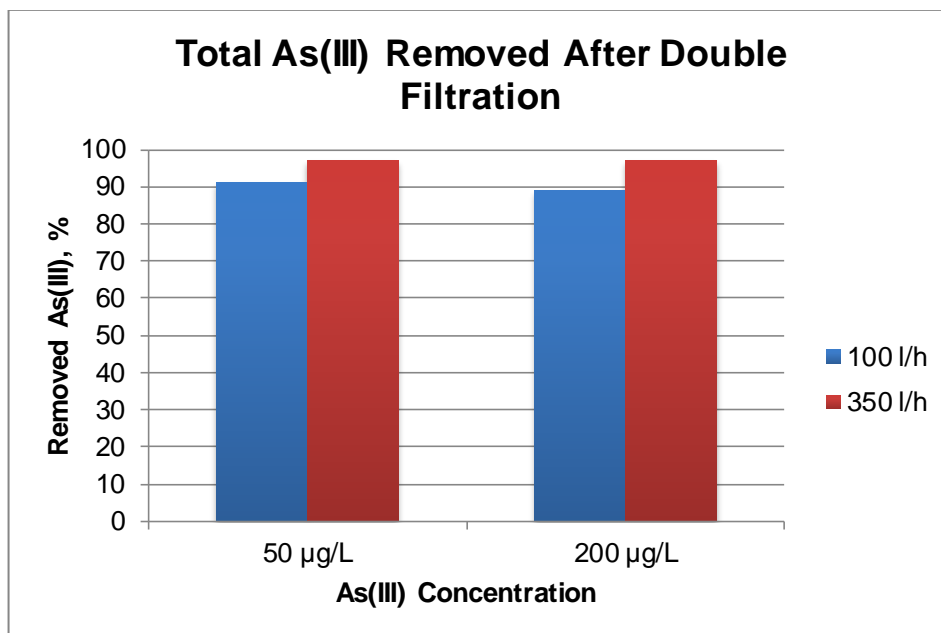


Figure 7. Total As(III) removed in Filtrate I

10.2 Experiments 5 – 8

The second batch of experiments involved the use of inlet water containing both As(III) and As(V). As in the previous experiments, inlet water containing about 100 µg/L As(III) and 100 µg/L As(V) was subjected to RO treatment operating at a filtrate flow of 100 and 350 L/h (as shown in Table 3). Table 6 gives percentages about the removed As(III) and As(V) in Filtrate I for each condition.

Table 6. Removed As(III) and As(V) in Filtrate I

Filtrate Flow [L/h]	Target Concentration [µg/L]	Actual Inlet Concentration [µg/L]	Average Filtrate I Concentration [µg/L]	Removed As(III) in Filtrate I	Re-moved As(V) in Filtrate I
100	100 µg/L As(III) + 100 µg/L As(V)	102 µg/L As(III) + 92 µg/L As(V)	32 µg/L As(III) + 3 µg/L As(V)	69%	97%
350	100 µg/L As(III) + 100 µg/L As(V)	87 µg/L As(III) + 115 µg/L As(V)	22 µg/L As(III) + 0 µg/L As(V)	75%	100%

The removal rates for As(III) in these two experiments are very similar to those from experiments where only As(III) was being treated (experiments 1-4). As expected, the majority of As(V) was removed. Table 7 presents the total As(III) and As(V) removal after double filtration for all conditions.

Table 7. Total As(III) and As(V) Removal Rates (Results of Double Filtration)

Filtrate Flow [L/h]	Inlet Concentration [µg/L]	Average Filtrate II Concentration [µg/L]	Removed As(III) in Filtrate II	Removed As(V) in Filtrate II	Total As(III) Removal after Double Filtration	Total As(V) Removal after Double Filtration
100	32 µg/L As(III) + 3 µg/L As(V)	11 µg/L As(III) + 1 µg/L As(V)	66%	67%	89%	99%
350	22 µg/L As(III) + 0 µg/L As(V)	< 6 µg/L As(III) + 0 µg/L As(V)	77%	100%	94%	100%

The results from double filtration, regardless of filtrate flow, show that As(V) is successfully removed by RO closely followed by As(III) with 94% total removal rate. Figures 8 - 10 provide a simpler comparison between the removal rates of As(V) and As(III) at different flow rates.

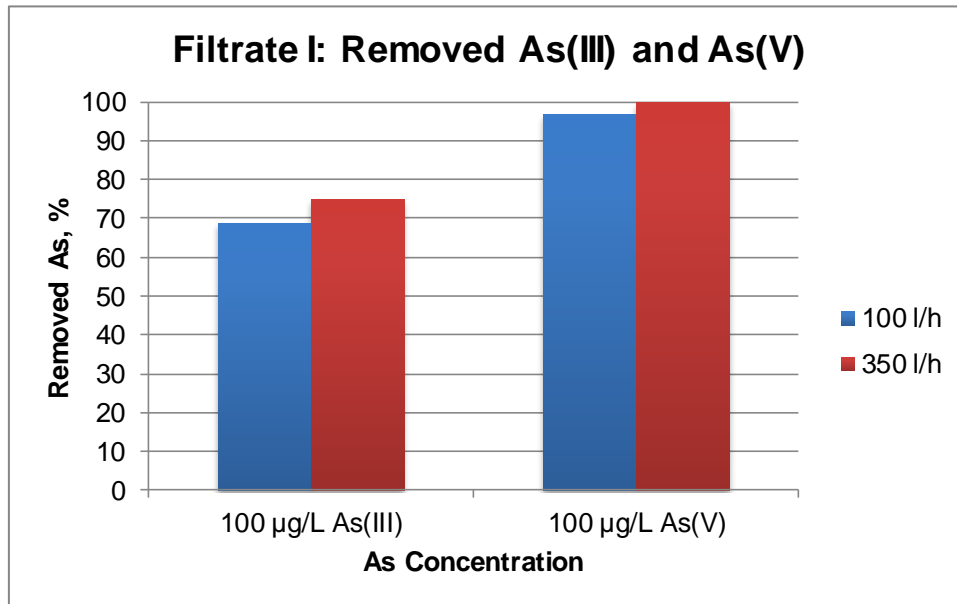


Figure 8. Total As(III) removed in Filtrate I

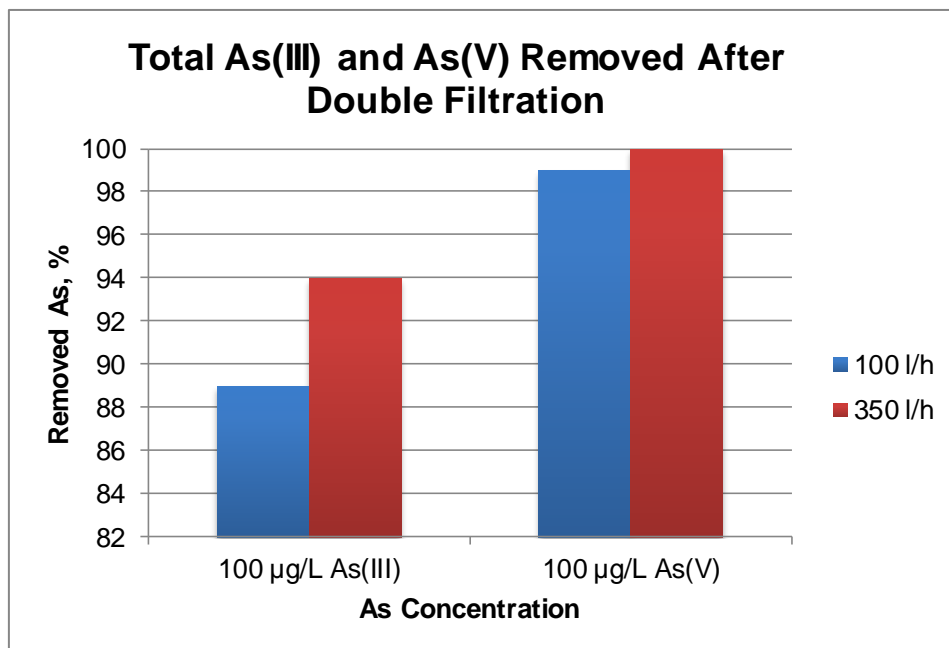


Figure 9. Total As(III) and As(V) Removed After Double Filtration

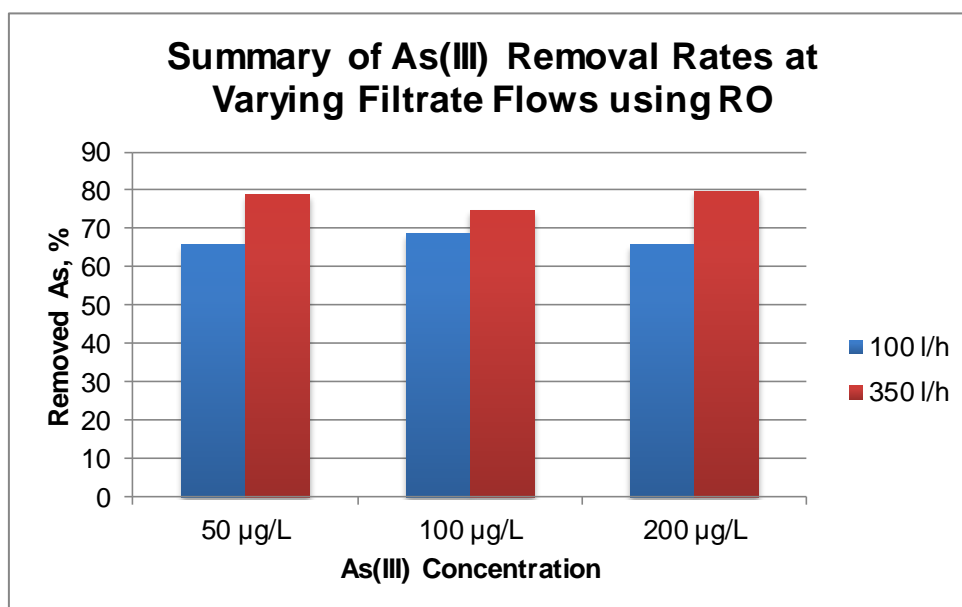


Figure 10. Summary of As(III) Removal at Varying Filtrate Flows and Concentrations Using RO.

In addition to using RO for As(III) and As(V) removal, two experiments using aeration treatment were carried out to determine the degree of conversion from As(III) to As(V). The conversion rates are given in Table 8.

Table 8. Conversion Rate of As(III) to As(V): Aeration Treatment

Total As [µg/L]	Aeration Treatment 2 hrs.		Aeration Treatment 24 hrs.		Total Conversion from As(III) to As(V)
	As(III) [µg/L]	As(V) [µg/L]	As(III) [µg/L]	As(V) [µg/L]	
102 µg/L As(III) + 92 µg/L As(V)	86	108	67	97	34%
242 µg/L As(III)	203	39	149	93	38%

Aeration treatment was carried out using aquarium aerators in 10 liters of contaminated water. Results show that despite 24 hours of mechanical aeration, As(III) to As(V) conversion is not rapid and would even be lower if the tested volume was only subject to atmospheric aeration. Results also suggest that conversion occurring due to aeration within the RO unit is highly unlikely since each experiment lasted for about one hour and water does not come into contact with the atmosphere once it is in the RO unit.

11 Conclusions and Suggestions

It is evident that removal of As(V) by reverse osmosis is successful without Double Filtration. All of the experiments conducted also suggest that the best operating point for the RO system is at a high filtrate flow. This is the case because at a high filtrate flow there is less pressure across the RO membrane. This in turn enables a better removal rate since pressure does not force contaminants into the permeate rendering the membrane's surface charge useless.

Additionally, the system provided by Malthe Winje DWS is built in such a way that it only allows improving or altering the performance of the RO unit by changing either the filtrate flow or the concentrate flow (which affect each other when either is changed). This is the case because there is a pump before the RO membrane that has only one fixed operating point that pumps 1 m³/h regardless of other conditions. In the case that there is too much pressure across the membrane due to low filtrate flow settings, instead of changing the amount of water pumped into the RO membrane, the system uses a magnetic valve that opens an emergency pipe that allows the release of water and decrease of pressure across the membrane. If the magnetic valve is not opened, then continued pressure across the membrane pushes contaminants through it. The results showed this occurs when the unit is operated at a filtrate flow of 100 L/h.

Since the membrane's surface charge is negative and As(V) is also negatively charged, when these come in contact with each other, they repel each other and As(V) is not allowed into the permeate flow. Naturally, when the filtrate flow is low and there is a constant sideways water flow entering the system, there is a larger pressure across the membrane that overcomes the force it would use to repel As(V). Thus, it is more likely that As(V) will be forced across the membrane and into the permeate flow. However, when the filtrate flow is high and the same amount of water is still entering the system, the membrane does not experience a large amount of external pressure since water can exit the system without as much force.

Operating this system at low filtrate flows not only decreases the removal rate of As(III), it also produces less clean water and can potentially shorten the life-span of the membrane. Ideally, it would be best to operate this RO unit with as high filtrate flow as the system allows.

With regard to double filtration, while it resulted in adequate As(III) removal results, it does not seem practical. All experiments at 350 L/h (which is now proven to be a better operation point) treated 1 m³ of water. This means that in one hour, the system treats less than 350 L out of 1000 L (that is about 650 liters of waste water). It is less than 350 because proper operation of the system requires flushing between treatment. The flushing continues roughly for two minutes and results in several liters of wastewater. Subjecting the remainder ~ 350 L to Double Filtration results in a product of about 123 liters of water. In total, of the initial volume of 1000 L, only 123 L would be accessible after Double Filtration.

Double filtration does not seem to be a viable solution for developing countries suffering from As contaminated waters especially since the maintenance and operational costs are high. It is also important to remember that RO treatment is an advanced treatment that is used for industrial applications since RO can produce ultra-pure water. Double filtration ensures that ultra-pure water is produced. Ultrapure water should not be used for drinking purposes, as drinking it is deadly.

In addition, aeration treatment results showed that mechanical aeration for 24 hours is still not efficient enough to convert more than half of As(III) to As(V). This suggests that mechanical aeration is a long process and that aeration is not an influencing factor within RO units especially if they are only operated a few hours a day.

In conclusion, it is difficult to suggest a universal treatment for the removal of As. When dealing specifically with the RO unit provided by Malthe Winje DWS, it is best to operate it at high filtrate flows and to be aware that as with all RO technology, As(V) removal is most successful. Even though results showed that there was about 80% removal of As(III), the resulting water is not adequate enough for consumption since the WHO standard is 10 µg/L. The results were very close to this number, but one must also consider that the water used in this experiment was already drinkable tap water. Sources of water containing As, especially groundwater, contain other contaminants that may affect the performance of the membrane and the removal efficiency of As.

It is difficult to suggest an appropriate solution because it highly depends of the region affected. I would suggest that places having adequate funds should use chemical oxidation of As(III) paired with RO treatment for As(V) removal. However, places lacking in

resources and trained operators will benefit most from mechanical or atmospheric aeration of As(III) even if it is time consuming.

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Appendix 1 – DOW FILMTEC LP-4040

Product Information



DOW FILMTEC™ Membranes

DOW FILMTEC Tape-Wrapped 4040 Elements for Commercial Applications

Features

A complete range of DOW FILMTEC™ 4040-size elements is available to meet a wide variety of customer needs for commercial applications, from the highest purity water to the lowest total system costs.

- DOW FILMTEC XLE-4040 is the most productive, lowest pressure RO membrane available, delivering the lowest total system cost.
- DOW FILMTEC LP-4040 delivers high quality water at low pressure operation. LP-4040 replaces many "first generation" low pressure membrane elements and will purify more water in many older systems, especially on cold water feeds.
- DOW FILMTEC TW30-4040 is the industry standard for reliable operation and production of the highest quality water.

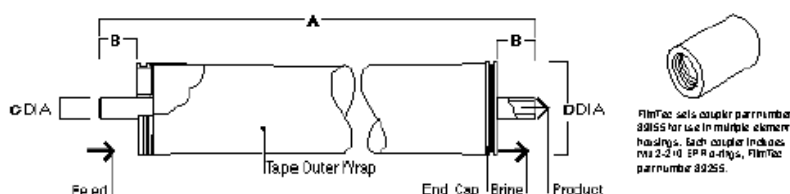
Tape-wrapped elements are built with the same high quality membranes and materials of construction as industrial elements, except for the hard outershell, and are more economical for commercial systems with one or two elements per housing.

Product Specifications

Product	Part number	Feed Spacer Thickness (mil)	Permeate Flow Rate gpd (m ³ /d)	Stabilized Salt Rejection (%)
XLE-4040	154546	28	2,600 (9.8)	99.0
LP-4040	212819	34	2,900 (11.0)	99.2
TW30-4040	80610	34	2,400 (9.1)	99.5

1. Permeate flow and salt rejection based on the following test conditions: 77°F (25°C), 15% recovery and applied pressure: 100 psig (6.9 bar) for XLE-4040, 145 psig (10 bar) for LP-4040 and 225 psig (15.5 bar) for TW30-4040. DOW FILMTEC TW30-4040 specifications are based on a 2,000 ppm NaCl feed stream. DOW FILMTEC LP-4040 and DOW FILMTEC XLE-4040 specifications are based on a 500 ppm NaCl feed stream.
2. Permeate flows for individual elements may vary $\pm 20\%$.
3. For the purpose of improvement, specifications may be updated periodically.

Figure 1



Product	Dimensions – Inches (mm)			
	A	B	C	D
XLE-4040	40.0 (1,016)	1.05 (26.7)	0.75 (19)	3.9 (99)
LP-4040	40.0 (1,016)	1.05 (26.7)	0.75 (19)	3.9 (99)
TW30-4040	40.0 (1,016)	1.05 (26.7)	0.75 (19)	3.9 (99)

1. Refer to DOW FILMTEC Design Guidelines for multiple-element systems.
2. DOW FILMTEC TW30-4040, DOW FILMTEC LP-4040 and DOW FILMTEC XLE-4040 elements fit nominal 4-inch I.D. pressure vessel.

1 inch = 25.4 mm

Operating Limits

• Membrane Type	Polyamide Thin-Film Composite
• Maximum Operating Temperature	113°F (45°C)
• Maximum Operating Pressure	600 psig (41 bar)
• Maximum Feed Flow Rate	14 gpm (3.2 m³/hr)
• Maximum Pressure Drop	13 psig (0.9 bar)
• pH Range, Continuous Operation ^a	2 - 11
• pH Range, Short-Term Cleaning (30 min.) ^b	1 - 13
• Maximum Feed Silt Density Index (SDI)	SDI 5
• Free Chlorine Tolerance ^c	<0.1 ppm

^a Maximum temperature for continuous operation above pH 10 is 95°F (35°C).

^b Refer to Cleaning Guidelines in specification sheet 609-23010.

^c Under certain conditions, the presence of free chlorine and other oxidizing agents will cause premature membrane failure. Since oxidation damage is not covered under warranty, DOW FILMTEC recommends removing residual free chlorine by pretreatment prior to membrane exposure. Please refer to technical bulletin 609-22010 for more information.

Important Information

Proper start-up of reverse osmosis water treatment systems is essential to prepare the membranes for operating service and to prevent membrane damage due to overfeeding or hydraulic shock. Following the proper start-up sequence also helps ensure that system operating parameters conform to design specifications so that system water quality and productivity goals can be achieved.

Before initiating system start-up procedures, membrane pretreatment, loading of the membrane elements, instrument calibration and other system checks should be completed.

Please refer to the application information literature entitled "Start-Up Sequence" (Form No. 609-02077) for more information.

Operation Guidelines

Avoid any abrupt pressure or cross-flow variations on the spiral elements during start-up, shutdown, cleaning or other sequences to prevent possible membrane damage. During start-up, a gradual change from a standstill to operating state is recommended as follows:

- Feed pressure should be increased gradually over a 30-60 second time frame.
- Cross-flow velocity at set operating point should be achieved gradually over 15-20 seconds.
- Permeate obtained from first hour of operation should be discarded.

General Information

- Keep elements moist at all times after initial wetting.
- If operating limits and guidelines given in this bulletin are not strictly followed, the limited warranty will be null and void.
- To prevent biological growth during prolonged system shutdowns, it is recommended that membrane elements be immersed in a preservative solution.
- The customer is fully responsible for the effects of incompatible chemicals and lubricants on elements.
- Maximum pressure drop across an entire pressure vessel (housing) is 30 psi (2.1 bar).
- Avoid static permeate-side backpressure at all times.

Regulatory Note

These membranes may be subject to drinking water application restrictions in some countries; please check the application status before use and sale.

DOW FILMTEC™ Membranes
For more information about DOW FILMTEC membranes, call the Dow Water & Process Solutions business:
North America: 1-800-447-4369
Latin America: (+55) 11-5188-9222
Europe: (+32) 3-450-2240
Pacific: +60 3 7958 3392
Japan: +813 5460 2100
China: +86 21 2301 1000
www.dowwaterandprocess.com

Notice: The use of this product in and of itself does not necessarily guarantee the removal of cysts and pathogens from water. Effective cyst and pathogen reduction is dependent on the complete system design and on the operation and maintenance of the system.

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Appendix 2 – Ion Exchange Resin DOWEX 21 K XLT

Product Information



DOWEX 21K XLT

A Uniform Particle Size, High Capacity, Strong Base Anion Exchange Resin for Mineral Processing Applications

Product	Type	Matrix	Functional group
DOWEX® 21K XLT	Type I strong base anion	Styrene-DVB, gel	Quaternary amine

Guaranteed Sales Specifications

Total exchange capacity, min.	eq/L	1.4
Water content	%	50 - 60
Bead size distribution		
Volume median diameter	µm	525 - 625
Uniformity coefficient, max.	%	1.1

Typical Physical and Chemical Properties

Ionic form as delivered		Cl ⁻
Total swelling (Cl ⁻ ⇒ OH ⁻), approx.	%	18 - 20
Whole uncracked beads, min.	%	90
Particle density, approx.	g/mL	1.08
Shipping weight, approx.	g/L lbs/ft ³	670 42

Recommended Operating Conditions

- Maximum operating temperature:
 - OH⁻ form 60°C (140°F)
 - Cl⁻ form 100°C (212°F)
- pH range 0 - 14
- Bed depth, min. 800 mm (2.6 ft)
- Flow rates:
 - Service/fast rinse 5 - 60 m/h (2 - 24 gpm/ft²)
 - Backwash See figure 1
 - Co-current regeneration/displacement rinse 1 - 10 m/h (0.4 - 4 gpm/ft²)
 - Counter-current regeneration/displacement rinse 5 - 20 m/h (2 - 8 gpm/ft²)
- Total rinse requirement 3 - 6 Bed volumes
- Regenerant:
 - Type NaCl/Carbonate
 - Temperature Ambient or up to 50°C (122°F) for silica removal
- Organic loading, max. 3g KMnO₄/L resin

Typical properties and applications

DOWEX 21K XLT type 1 strong base anion resin has excellent kinetics, excellent regeneration efficiency and outstanding physical stability. The uniform sized beads give maximum performance for all packed bed systems. DOWEX 21K XLT represents the state-of-the-art in mineral processing resins.

Packaging

5 cubic foot fiber drums

Figure 1. Pressure Drop vs. Flow Rate

For DOWEX 21K Resins, Cl, 77 deg. F

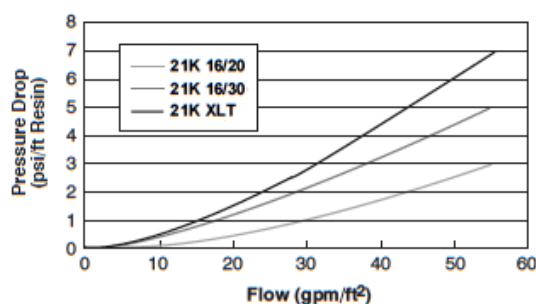
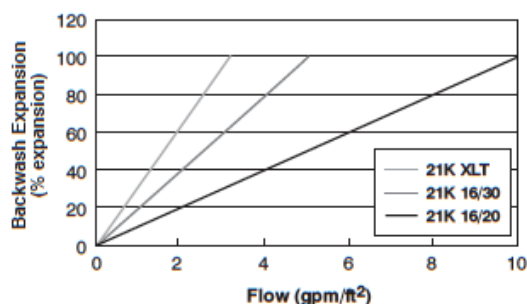


Figure 2. Backwash Expansion vs. Flow Rate

For DOWEX 21K Resins, Cl, 77 deg. F



DOWEX Ion Exchange Resins

For more information about DOWEX resins, call the Dow Liquid Separations business:

North America: 1-800-447-4369
 Latin America: (+55) 11-5188-9222
 Europe: (+32) 3-450-2240
 Pacific: +60 3 7958 3392
 Japan: +813 5460 2100
 China: +86 21 2301 9000
<http://www.dowex.com>

Warning: Oxidizing agents such as nitric acid attack organic ion exchange resins under certain conditions. This could lead to anything from slight resin degradation to a violent exothermic reaction (explosion). Before using strong oxidizing agents, consult sources knowledgeable in handling such materials.

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Appendix 3 – Experimental Procedure and Supplementary Notes

Experimental Design

The purpose of this experiment is to determine whether double filtration by reverse osmosis increases the removal efficiency of As(III). To do this, the effects of flow rate and concentration, during double filtration will be explored.

Reverse Osmosis Membrane: DOW LP 4040

Table 1. Experimental Conditions

Flow	Concentration	pH	Number of Filtrations
100 L/h	50 µg/L As(III)	Constant	2
350 L/h	200 µg/L As(III)		

For clarification purposes, each experiment and sample that will be sent to the laboratory is labeled as follows:

Table 2. Conditions per Experiment.

Experiment	Conditions*	
1	100 L/h	50 µg/L As(III)
2	100 L/h	200 µg/L As(III)
3	350 L/h	50 µg/L As(III)
4	350 L/h	200 µg/L As(III)

* All experiments are subject to double filtration (Filtration II).

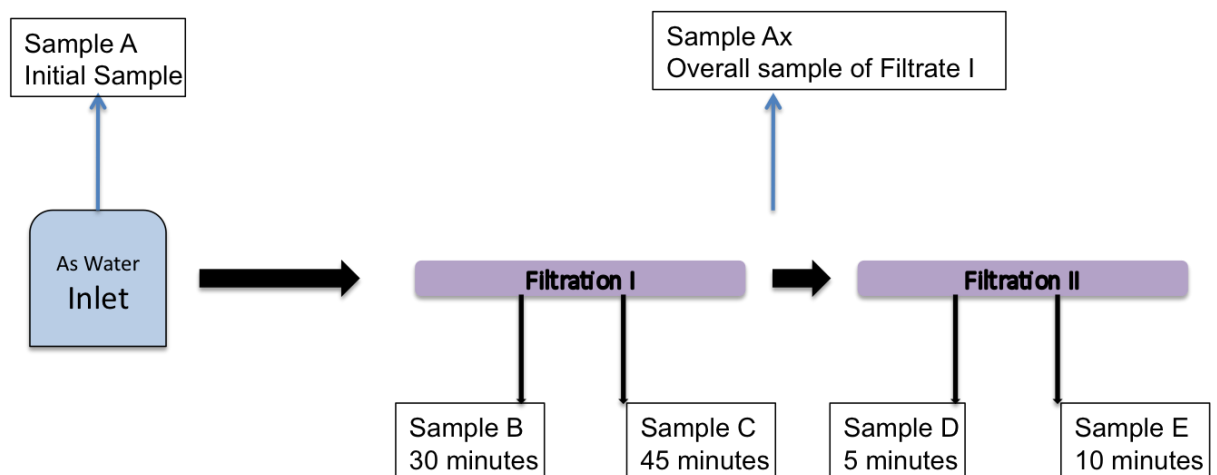
Table 3. Label per Sample Condition Being Analyzed.

Sample	Condition	
A	Initial Sample of Intake	Before Filtration I
B	Filtration I	30 minutes
C	Filtration I	45 minutes
Ax	Overall sample of Filtration I	End of Filtration I
C	Filtration II	5 minutes
D	Filtration II	10 minutes

Procedure

1. To avoid excess use of As concentrated water, first run the RO system with only water to ensure normal operation (flushing of the membrane).
2. Use the tap water to fill a 1 m³ container. Include the corresponding As solution and ensure it is properly mixed with the water. This is the inlet water for Filtration I.
3. Collect a 50 ml sample of the inlet water.
4. Start the RO system to begin Filtration I. The filtrate from Filtration I should be collected for later use (Filtration II).
5. Collect a 50 ml sample in 30 minutes.
6. Collect a 50 ml sample in 45 minutes.
7. Stop the RO system and flush the membrane with water.
8. Collect a 50 ml sample of the filtrate water.
9. Use the filtrate from Filtration I as inlet water.
10. Start the RO system to begin Filtration II. Collect the filtrate to be treated as waste separately.
11. Collect a 50 ml Sample in 5 minutes.
12. Collect a 50 ml sample in 10 minutes.
13. Stop the RO system and flush the membrane with water.

Experiment and Sample Schematics



Experiment Schedule and Procedure Charts

Thursday, 10 May 2012

Experiment	Conditions
1	100 L/h 50 µg/L As(III)

Table 4. Sample Checklist

Sample	Condition	
A	Initial Sample of Intake	Before Filtration I
B	Filtration I	30 minutes
C	Filtration I	45 minutes
Ax	Overall sample of Filtration I	End of Filtration I
C	Filtration II	5 minutes
D	Filtration II	10 minutes

Table 5. Outflow Pressure and Inlet Conductivity

Sample	Outflow Pressure [MPa]				Inlet Conductivity [µS/cm]
	PI1	PI2	PI3	PI4	
B	0.34	0.33	1.4	1.5	16
C	0.34	0.33	1.5	1.5	17
D	0.30	0.28	0.50	0.50	10
E	0.32	0.30	0.60	0.70	12

Remarks: In order to have enough filtrate for Filtration II, two 1000 L tanks were used for Filtration I.

Thursday, 10 May 2012

Experiment	Conditions
2	100 L/h 200 µg/L As(III)

Table 6. Sample Checklist

Sample	Condition	
A	Initial Sample of Intake	Before Filtration I
B	Filtration I	30 minutes
C	Filtration I	45 minutes
Ax	Overall sample of Filtration I	End of Filtration I
C	Filtration II	5 minutes
D	Filtration II	10 minutes

Table 7. Outflow Pressure and Inlet Conductivity

Sample	Outflow Pressure [MPa]				Inlet Conductivity [µS/cm]
	PI1	PI2	PI3	PI4	
B	0.34	0.33	1.3	1.4	17
C	0.33	0.33	1.5	1.5	16
D	0.36	0.30	1.2	1.2	15
E	0.32	0.30	1.2	1.2	12

Remarks: In order to have enough filtrate for Filtration II, two 1000 L tanks were used for Filtration I.

Friday, 11 May 2012

Experiment	Conditions
3	350 L/h 50 µg/L As(III)

Table 8. Sample Checklist

Sample	Condition	
A	Initial Sample of Intake	Before Filtration I
B	Filtration I	30 minutes
C	Filtration I	45 minutes
Ax	Overall sample of Filtration I	End of Filtration I
C	Filtration II	5 minutes
D	Filtration II	10 minutes

Table 9. Outflow Pressure and Inlet Conductivity

Sample	Outflow Pressure [MPa]				Inlet Conductivity [µS/cm]
	PI1	PI2	PI3	PI4	
B	0.33	0.30	1.5	1.6	5
C	0.32	0.30	1.5	1.6	6
D	0.29	0.26	1.5	1.5	3
E	0.29	0.28	1.5	1.5	3

Friday, 11 May 2012

Experiment	Conditions
4	350 L/h 200 µg/L As(III)

Table 10. Sample Checklist

Sample	Condition	
A	Initial Sample of Intake	Before Filtration I
B	Filtration I	30 minutes
C	Filtration I	45 minutes
Ax	Overall sample of Filtration I	End of Filtration I
C	Filtration II	5 minutes
D	Filtration II	10 minutes

Table 11. Outflow Pressure and Inlet Conductivity

Sample	Outflow Pressure [MPa]				Inlet Conductivity [µS/cm]
	PI1	PI2	PI3	PI4	
B	0.34	0.32	1.6	1.6	6
C	0.34	0.31	1.5	1.6	6
D	0.32	0.30	1.7	1.8	3
E	0.32	0.30	1.7	1.8	3

Appendix 4 – Experimental Procedure and Supplementary Notes (Batch 2)

Experimental Design

The purpose of this experiment is to determine whether double filtration by reverse osmosis increases the removal efficiency of As(III). To do this, the effects of flow rate and concentration, during double filtration will be explored.

Reverse Osmosis Membrane: DOW LP 4040

Table 1. Experimental Conditions

Flow	Concentration	pH	Number of Filtrations
100 L/h 350 L/h	100 µg/L As(III) + 100 µg/L As(V)	Constant	2

For clarification purposes, each experiment and sample that will be sent to the laboratory is labeled as follows:

Table 2. Conditions per Experiment.

Experiment	Conditions*	
1	100 l/h	100 µg/L As(III) + 100 µg/L As(V)
2	350 l/h	100 µg/L As(III) + 100 µg/L As(V)

* All experiments are subject to double filtration (Filtration II).

Table 3. Label per Sample Condition Being Analyzed.

Sample	Condition		
A	Initial Sample of Intake	Before Filtration I	50 ml, 500 ml
A_1	Sample A through ion exchange resin	After sample A	50 ml
B	Filtration I	30 minutes	50 ml, 500 ml
C	Sample B through ion exchange resin	After Sample B	50 ml
D	Filtration I	45 minutes	50 ml, 500 ml
E	Sample D through ion exchange resin	After Sample D	50 ml
Ax	Overall sample of Filtration I	End of Filtration I	50 ml, 500 ml
Ax_1	Sample Ax through ion exchange resin	After Sample Ax	50 ml
F	Filtration II	5 minutes	50 ml, 500 ml
G	Sample F through ion exchange resin	After Sample F	50 ml
H	Filtration II	10 minutes	50 ml, 500 ml
I	Sample H through ion exchange resin	After sample H	50 ml
J	Aeration Treatment	2 hours	500 ml
K	Sample J through ion exchange resin	After Sample J	50 ml
L	Aeration Treatment	24 hours	500 ml
M	Sample L through ion exchange resin	After Sample L	50 ml

Reverse Osmosis Unit Procedure

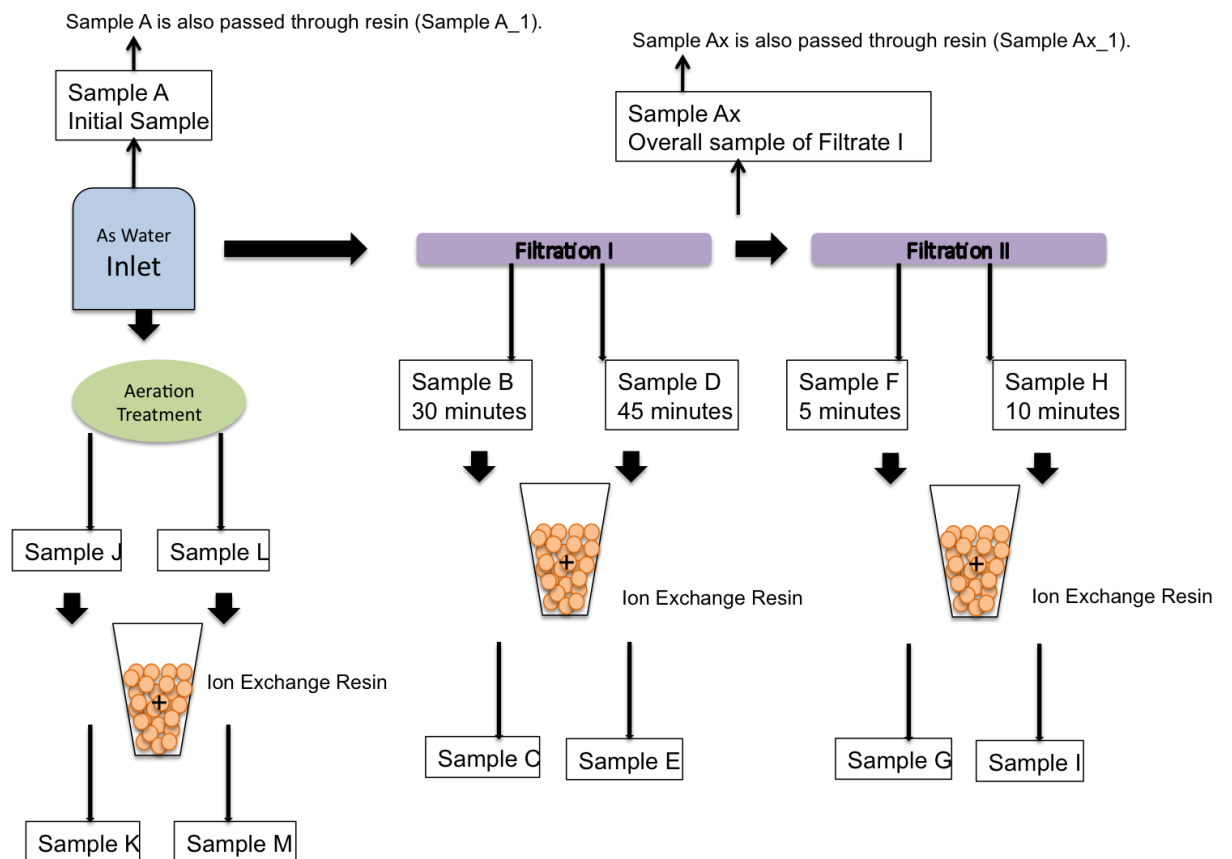
14. To avoid excess use of As concentrated water, first run the RO system with only water to ensure normal operation (flushing of the membrane).
15. Use the tap water to fill a 1 m³ container. Include the corresponding As solution and ensure it is properly mixed with the water. This is the inlet water for Filtration I.
16. Collect a 50 ml and 500 ml sample of the inlet water.
17. Pass the 500 ml sample through the ion exchange resin. From the product collect 50 ml sample.
18. Collect 10 L for aeration treatment.
19. Start the RO system to begin Filtration I. The filtrate from Filtration I should be collected for later use (Filtration II).
20. Collect a 50 ml and 500 ml sample in 30 minutes.
21. Pass the 500 ml sample through the ion exchange resin. From the product, collect 50 ml.
22. Collect a 50 ml and 500 ml sample in 45 minutes.
23. Pass the 500 ml sample through the ion exchange resin. From the product, collect 50 ml.
24. Stop the RO system and flush the membrane with water.
25. Collect an overall sample of 50 ml and 500 ml of Filtrate I.
26. Pass the 500 ml sample through the ion exchange resin. From the product, collect 50 ml.
27. Use the filtrate from Filtration I as inlet water for Filtration II.
28. Start the RO system to begin Filtration II. Collect the filtrate to be treated as waste separately.
29. Collect a 50 ml and 500 ml sample in 5 minutes.
30. Pass the 500 ml sample through the ion exchange resin. From the product, collect 50 ml.
31. Collect a 50 ml and 500 ml sample in 10 minutes.
32. Pass the 500 ml sample through the ion exchange resin. From the product, collect 50 ml.
33. Stop the RO system and flush the membrane with water.

Aeration Procedure

Do only once since concentration is the same for Experiment 2 and 3.

1. Place the aquarium aerator in the 10 L sample collected previously or prepared. Begin aeration.
2. Collect a 500 ml sample in 2 hours and pass it through the ion exchange resin. From the product, collect a 50 ml sample.
3. Collect a 500 ml sample in 24 hours and pass it through the ion exchange resin. From the product, collect a 50 ml sample.

Experiment and Sample Schematics



Experiment Schedule and Procedure Charts

Tuesday, 29 May 2012

Experiment	Conditions
1	100 L/h 100 µg/L As(III) + 100 µg/L As(V)

Table 4. Sample Checklist

Sample	Condition		
A	Initial Sample of Intake	Before Filtration I	50 ml, 500 ml
A_1	Sample A through ion exchange resin	After sample A	50 ml
B	Filtration I	30 minutes	50 ml, 500 ml
C	Sample B through ion exchange resin	After Sample B	50 ml
D	Filtration I	45 minutes	50 ml, 500 ml
E	Sample D through ion exchange resin	After Sample D	50 ml
Ax	Overall sample of Filtration I	End of Filtration I	50 ml, 500 ml
Ax_1	Sample Ax through ion exchange resin	After Sample Ax	50 ml
F	Filtration II	5 minutes	50 ml, 500 ml
G	Sample F through ion exchange resin	After Sample F	50 ml
H	Filtration II	10 minutes	50 ml, 500 ml
I	Sample H through ion exchange resin	After sample H	50 ml
J	Aeration Treatment	2 hours	500 ml
K	Sample J through ion exchange resin	After Sample J	50 ml
L	Aeration Treatment	24 hours	500 ml
M	Sample L through ion exchange resin	After Sample L	50 ml

Table 5. Outflow Pressure and Inlet Conductivity

Sample	Outflow Pressure [MPa]				Inlet Conductivity [µS/cm]
	PI1	PI2	PI3	PI4	
B	0.32	0.28	1.48	1.5	9
D	0.32	0.28	1.48	1.5	9
F	0.32	0.28	1.48	1.5	9
H	0.32	0.28	1.48	1.5	9

Tuesday, 29 May 2012

Experiment	Conditions
3	350 L/h 100 µg/L As(III) + 100 µg/L As(V)

Table 6. Sample Checklist

Sample	Condition		
A	Initial Sample of Intake	Before Filtration I	50 ml, 500 ml
A_1	Sample A through ion exchange resin	After sample A	50 ml
B	Filtration I	30 minutes	50 ml, 500 ml
C	Sample B through ion exchange resin	After Sample B	50 ml
D	Filtration I	45 minutes	50 ml, 500 ml
E	Sample D through ion exchange resin	After Sample D	50 ml
Ax	Overall sample of Filtration I	End of Filtration I	50 ml, 500 ml
Ax_1	Sample Ax through ion exchange resin	After Sample Ax	50 ml
F	Filtration II	5 minutes	50 ml, 500 ml
G	Sample F through ion exchange resin	After Sample F	50 ml
H	Filtration II	10 minutes	50 ml, 500 ml
I	Sample H through ion exchange resin	After sample H	50 ml

Table 7. Outflow Pressure and Inlet Conductivity

Sample	Outflow Pressure [MPa]				Inlet Conductivity [µS/cm]
	PI1	PI2	PI3	PI4	
B	0.32	0.31	1.64	1.7	8
D	0.33	0.30	1.67	1.7	7
F	0.30	0.28	1.35	1.4	3
H	0.03	0.28	1.35	1.4	3

Wednesday, 30 May 2012

Experiment	Conditions
4	10 L of 200 µg/L As(III) Aeration treatment for a total of 24 hours

Table 8. Sample Checklist

Sample	Condition		
A	Initial Sample of Intake	Before Filtration I	50 ml
B	Aeration Treatment	2 hours	500 ml
C	Sample B through ion exchange resin	After Sample B	50 ml
D	Aeration Treatment	24 hours	500 ml
E	Sample D through ion exchange resin	After Sample D	50 ml

